ELECTRIC PROPULSION POINTING MECHANISM FOR BEPI COLOMBO

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ABSTRACT

Since 15 years the development of Electric Propulsion Pointing Mechanisms for commercial and scientific satellite applications is a key-product activity for RUAG Space in Vienna.

As one of the most innovative EP mechanisms presently under development in Vienna this paper presents the Electric Propulsion Thruster Pointing Mechanism for the Bepi Colombo Mission.

RUAG Space delivers the mechanism assembly, consisting of the mechanisms and the control electronics.

1. GENERAL SPECIFICATIONS

The Bepi Colombo Mercury Transfer Module will be equipped with four Electric Propulsion Thrusters. For each of these thrusters one Thruster Pointing Mechanism (TPM) is foreseen.
The following figure presents the thruster floor of the spacecraft, equipped with the TPMs and the thrusters:

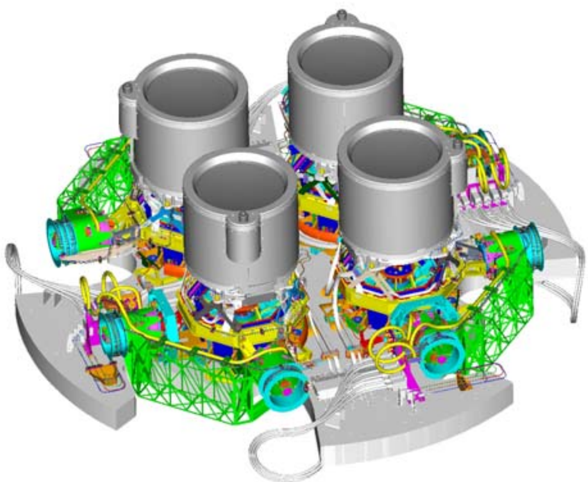

Figure 1. TPMs with Thrusters and Thruster Floor.

The mechanism shall support the QinetiQ T6 thruster during launch and protect it against launch and separation loads via a load attenuation system. Once released it shall point the thruster accurately and provide support for the high voltage power supply and the Xenon gas supply of the thruster.

Main parameters of the mechanism:

Pointing Range - Axis 1	+21° / -8°
Pointing Range - Axis 2	+21° / -8°
Pointing accuracy	better than 0.2°
Resistive torque	5.6 Nm (thruster harness and piping)
Supported Mass	10 kg (Thruster, Harness, Sun-shield)
Thruster CoG Height	130 mm
Mechanism Mass	11.0 kg (w/o Sun-shield)
Main Dimensions (LxWxH):	660 x 660 x 223 mm
Stiffness	65 Hz (stowed configuration) 6 Hz (deployed configuration)
Temperature	-40°C to +100°C for TPM components
Drive Unit	2 Stepper motors Power supply 26V
Release of HDRM	Non-explosive resetable device (1x, central)
Mechanical I/F to S/C	8+1 bolts M5
Life time	7 years storage, 6.6 years in orbit

The configuration of the mechanism is a cross cardan type, with its rotation axes intersecting in the thruster center line.

The design-driving requirements are:

- Minimized dynamic load and shock load introduction into the thruster, induced by launch loads, separation loads, and thruster release,
- Pointing capability in both directions around the stowed configuration. The stowed configuration is required to be between the two extremes of the pointing range, and
- Very high reliability,
- Minimized mechanism mass.

This paper will outline the design solutions for these design driving requirements.

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2. DESIGN TO MINIMIZE THRUSTER LOADS

The mechanism not only has to point the thruster, but also to protect it against the launch loads. The selected electric propulsion thruster (gridded ion thruster type) is very delicate and must be protected from excessive vibration load levels and from shock load.

2.1. Lateral Load Accommodation

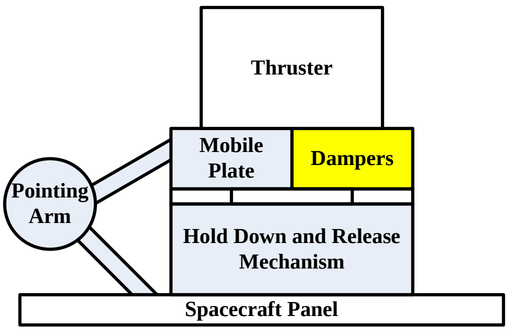
It is specified that the thruster shall not be exposed to considerable lateral random loads in frequency regions above 100 Hz. To de-couple the dynamic mechanical environment of the thruster from the dynamic load input coming from the spacecraft, the mechanism is designed to a first fundamental Eigenfrequency of 65 Hz in lateral direction. The spacecraft panel itself is quite stiff in lateral direction, so the dynamic load from the spacecraft is fully transmitted into the mechanism. However within the mechanism there occurs the desired load attenuation in the thruster's critical frequency range but also an unwanted amplification in the lower Eigenfrequency band. By "tuning" the mechanism to this low Eigenfrequency, the thruster is protected from the dynamic lateral load environment coming from the spacecraft.

2.2. Need for Dampers and Optimized Configuration

The selected low first fundamental frequency would lead to an unacceptable high amplification during sine load application and lead to unacceptable high thruster loads at these frequencies, even if the thruster is more robust in this frequency band. So a damping system had to be introduced. The damping system is made of dampers which are placed on the load-path of the mechanism in its stowed configuration.

The following configurations were studied:

a) The damping elements located in parallel to the strained elements:

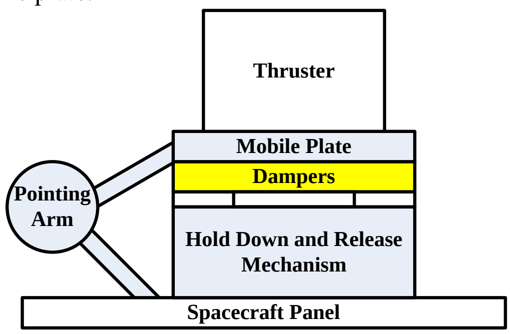


This configuration was used in the RUAG Thruster Pointing Mechanisms for Artemis (Ref. 1-3) and in the RUAG Thruster Pointing Mechanism for Eurostar 3000 (Ref. 4). The advantages of this configuration are that the dampers are not directly in the load path, neither in the stowed configuration, nor in the deployed configuration, consequently no adverse aging effects of physical properties need to be considered - and the mass efficiency of this design.

In the case of the Bepi Colombo mechanism this configuration turned out to be not feasible as the necessary high damping factor could not be achieved by such a parallel configuration of strained elements and damping elements.

Consequently the following damping concepts have been investigated:

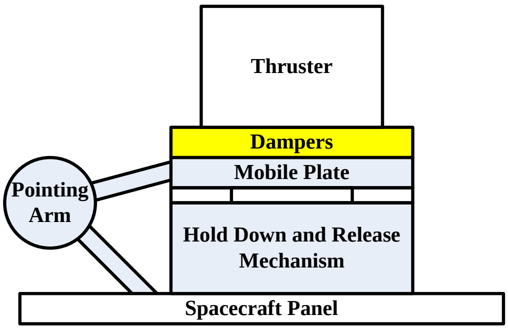
b) The damping elements are located in-between the hold-down and release-mechanism and the mobile plate, the pointing arm attached to the spacecraft panel and the mobile plate.



In this configuration the dampers are directly in the load path of the stowed configuration, but off the load path in the deployed configuration, thus making also this design in-sensitive to aging of the damper material. The dampers are remote from the spacecraft panel. The dampers have limited thermal conductance to the spacecraft panel which is well thermally controlled. This leads to higher temperature variations within the dampers which may lead to changing material properties of the dampers if elastomer types are used.

The advantage of this configuration is that the dampers are out of the mechanical load path in the deployed configuration. Assuming a certain outer diameter of the damper arrangement, and assuming a given lateral Eigenfrequency, softer dampers are needed which in turn reduces the out-of-plane mode of the assembly, giving a different load to the thruster compared to an arrangement where the dampers are located close to the spacecraft panel.

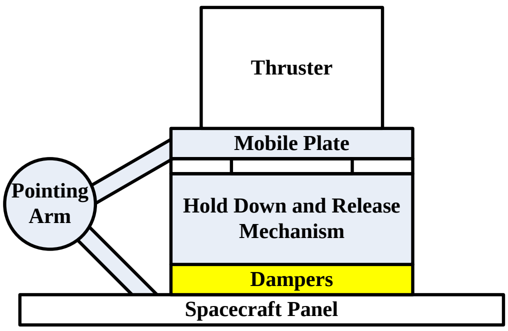
c) The damping elements are located in-between the mobile plate and release -mechanism and the mobile plate, the pointing arm attached to the spacecraft panel and the mobile plate.



In this configuration the dampers are directly in the load path both of the stowed and of the deployed configuration. The dampers are close to the thruster. So the dampers are exposed to high temperature during operation. The long term stability of the dampers under such a thermal load may be an issue.

The advantage of such a configuration could be that the dampers could fulfill two functions. Firstly the damping characteristics, but secondly they could also be used as an isostatic mount for the thruster, compensating the different thermal expansion of the mobile plate and of the thruster during thruster operation. This could save some mass of the mechanism.

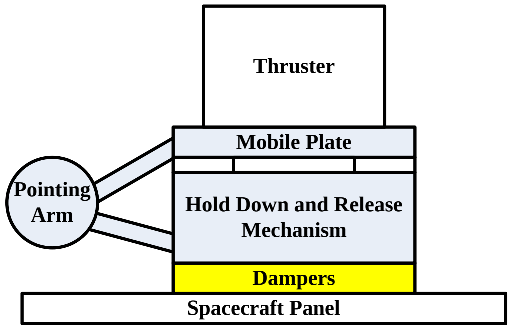
d) The damping elements are located below the hold-down and release-mechanism, the pointing arm is attached to the spacecraft panel:



In this configuration the dampers are directly in the load path of the stowed configuration, but off the load path in the deployed configuration, again making this design in-sensitive to aging of the damper material.

The dampers are directly connected to the spacecraft panel, providing good thermal control of the dampers. However the low lateral Eigenfrequency of the mechanism causes large deflections of the mobile plate relative to the spacecraft panel and would require a pointing arm which could accommodate large deflections.

e) The damping elements are located below the hold-down and release-mechanism, the pointing arm is attached to the hold down and release mechanism:



In this configuration the dampers are also directly in the load path of the stowed configuration, but also in the load path in the deployed configuration, making this design sensitive to aging of the damper material which then has to be carefully assessed. Aging of the damper material can be an issue if elastomere dampers are used.

The advantage of this configuration is the low deflection of the pointing arm during dynamic load application, allowing a simple and low mass design of this arm. Another advantage is that the dampers are directly connected to the spacecraft panel, providing good thermal control of the dampers as they follow the thermal control of the spacecraft itself which is an issue especially on the Bepi Colombo mission to Mercury with its demanding temperature environment.

For the above reasons, this latter configuration was selected for the Bepi Colombo Electric Propulsion Thruster Pointing Mechanism, and implemented as shown in the following figure:

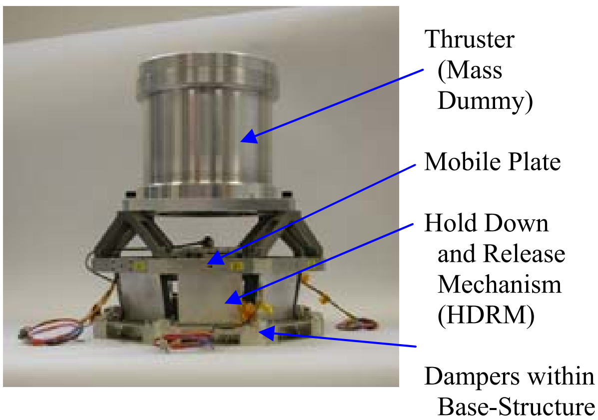


Figure 2. TPM Structure (Breadboard Model)

The pointing arm is not shown in above figure.

2.3. Out-of-plane Load Accommodation

The above described lateral main modes of the assembly are mainly bending modes around the dampers, which are the soft element within the assembly. The damper stiffness is tuned to adjust the lateral main mode of the assembly to the desired 65 Hz Eigenfrequency. With a given damper arrangement outer diameter, this defines the stiffness of the dampers and through this also the out-of-plane stiffness of the assembly is defined.

The large distance between the dampers and the center of gravity of the assembly still allows for a relatively stiff damper compared to a configuration where the damper is located closer to the thruster. This stiffness causes an out-of plane fundamental frequency of more than 200 Hz. Such a high stiffness in out-of-plane direction is acceptable, as the spacecraft panel itself has low stiffness in out-of-plane direction and as such is acting as a low-pass filter for the vibration loads coming from the spacecraft. The coupled analysis confirms this comprehensive approach that includes the properties of the spacecraft structure in to the mechanism design concept. For testing of the mechanism on mechanism level respective notching is applied.

2.4. Shock Loads

The above described concept of de-coupling of frequencies in order to minimize loads on the thruster in any direction for random vibration also minimizes the shock transmission into the thruster. Whereas the dampers are not very effective in attenuation of shock loads, which can be derived from theory and which was confirmed also during the mechanism test campaigns, the concept of de-coupling of frequencies is very well attenuating the shock loads propagated through the spacecraft into the thruster.

2.5. Damper Selection and Design

Elastomer dampers were selected for their superior damping rate. The drawback of using elastomer dampers is that they make the analysis of the mechanism very complex as they have a non-linear behavior related to the following parameters:

- high temperature dependability of the stiffness, stiffness increases with lower temperatures,
- high load dependability of their stiffness, stiffness decreases at higher loads, and
- high frequency dependability of their stiffness, stiffness increases with higher frequency.

The structural analysis of the mechanism must cover the worst case combinations that can result of these non-linearities.

3. POINTING ARM DESIGN

For the Bepi Colombo Electric Propulsion Thruster Pointing Mechanism a novel design of a light weight pointing arm was developed.

3.1. Requirements

The pointing arm is connected with the base of the Hold-Down and Release Mechanism and the Mobile Plate. During the launch phase, when the Hold-Down and Release Mechanism is locked, it is off the primary load path but it is loaded by relative movements between its attachment points. After release of the Mobile Plate the pointing arm becomes part of the main load path, and has to support the mobile plate with the attached thruster. It has to provide the necessary stiffness to attain the pointing accuracy and to comply with the Eigenfrequency requirement on the mechanism in its deployed configuration. A high stiffness design of the arm is necessary.

To sustain the random loads without significant frequency coupling, no local modes are allowed with less than 300 Hz. With the given distance of the attachment points, and the envelope constraints a slender design is required. Buckling is an issue which has to be prevented by the design.

On the two ends of the pointing arm the geared actuators are mounted. The pointing arm must provide an isostatic interface to the actuators, as the pointing arm is made of Aluminum alloy whereas the actuator housings are made of Titanium alloy. The different thermal expansion has to be compensated by the pointing arm's interfaces to the actuators. Also thermal distortion shall be kept to a minimum.

The pointing arm shall not be strained in the stowed configuration. The attachment points are manufactured to certain manufacturing tolerances, so the pointing arm must have alignment capability for strain-free attachment. The actuators cannot be used for rotational alignment because their reference positions are defined relative to the stowed position so the pointing arm has to have alignment capabilities in 6 degrees of freedom.

The mechanism harness and the thruster piping are routed along the pointing arm. The support of this harness and piping has to be incorporated into the pointing arm design.

The above requirements have to be fulfilled while still contributing low mass to the mechanism. This low mass design requirement applies for the arm structure itself but also for the interface elements to the adjacent parts.

The chosen design of the pointing arm fulfills above requirements while still having remarkable low manufacturing cost.

3.2. Design

The pointing arm consists of a framework made of Aluminum alloy. An integral design was chosen meaning that the whole arm is manufactured from one solid block of Aluminum Alloy.

Figure 3. Pointing Arm

The framework structure is designed having a large cross section of thin walled struts. The framework structure also comprises of diagonal struts which increase local Eigenfrequencies and prevent buckling of the struts. This frame-work design provides excellent mass efficiency and high stiffness.

The strength of the pointing arm allows release of the mechanism under earth gravity (1g) which allows simple testing without the need of off-load devices for on-ground release.

On both ends of the arm an interface to a geared actuator is machined. This interface is slotted, making it isostatic to comply with the different thermal expansion of the Aluminum alloy structure and the Titanium Alloy housing of the geared actuators. The bolt hole arrangement for the actuator interface bolts allows adjustment of the pointing arm onto the geared actuators compensating manufacturing tolerances of within the tolerance chains between the actuators and the pointing arm which forms a parallel path. The integral design of the interfaces to the geared actuators is a very light weight solution with very good stiffness.

The central nodes of the struts of the top surface have extrusions with threads for the mechanism harness clamps and the pipe clamps for harness and pipe routing. Also these extrusions are an integral part of the pointing arm.

The following figure shows the pointing arm attached to the hold-down and release mechanism (HDRM).

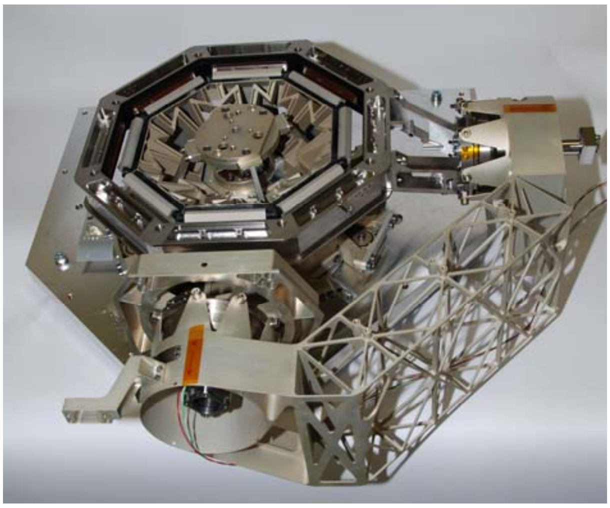


Figure 4. Pointing Arm attached to the HDRM

The pointing arm performance was confirmed during the vibration, shock and release testing of the mechanism.

A patent of the pointing arm covering both the design and the manufacturing process is pending.

4. HOLD-DOWN AND RELEASE MECHANISM

For the Bepi Colombo Electric Propulsion Thruster Pointing Mechanism a spring loaded knuckle-lever system which in essence forms a “frangible pipe” was selected for the Hold-Down and Release Mechanism (HDRM).

4.1. Requirements

In launch configuration the thruster has to be stowed on a plane which is parallel to the spacecraft panel. Once released, pointing capability is required in all directions around this stowed configuration.

To allow the described design of the decoupling of the main modes, the HDRM itself has to be very stiff in stowed configuration. It also has to transmit considerable loads especially caused by lateral loads together with the distant center of gravity of the thruster. Low height of the HDRM reduces this load.

The thruster must not be exposed to any significant shock from the release of the hold-down pre-load. Even if a low shock non explosive device is used, a careful design of the release mechanism is necessary to protect the thruster from release shocks.

For highest reliability and cost reduction, the number of release actuators should be minimized. A single release actuator solution was preferred.

For convenient integration on the spacecraft, a design as a single self-standing unit was preferred . So the mechanism can be integrated to the spacecraft as a whole.

4.2. Design

The HDRM consists of an arrangement of eight vertical spring plates which connect the ring-shaped base structure with the ring shaped mobile plate forming a pipe-like structure that supports the thruster rigidly.

The vertical spring plates are bolted to the base structure. On their upper end they have V-shaped release interfaces to the mobile plate. These are loaded by horizontal springs. The pre-load of the horizontal springs ensures contact between the vertical spring plates and the mobile plates under all load cases.

The horizontal springs are connected to a central plate. This central plate is attached to a release actuator. The horizontal springs are arranged in a slight angle so that they mainly load the vertical spring plates in radial direction, but there is also an axial force. This axial force is small compared to the radial force following a knuckle lever principle. Once the release actuator is actuated, this axial force drives the central plate downwards and the vertical plates return inwards, into their relaxed configuration, and release the mobile plate.

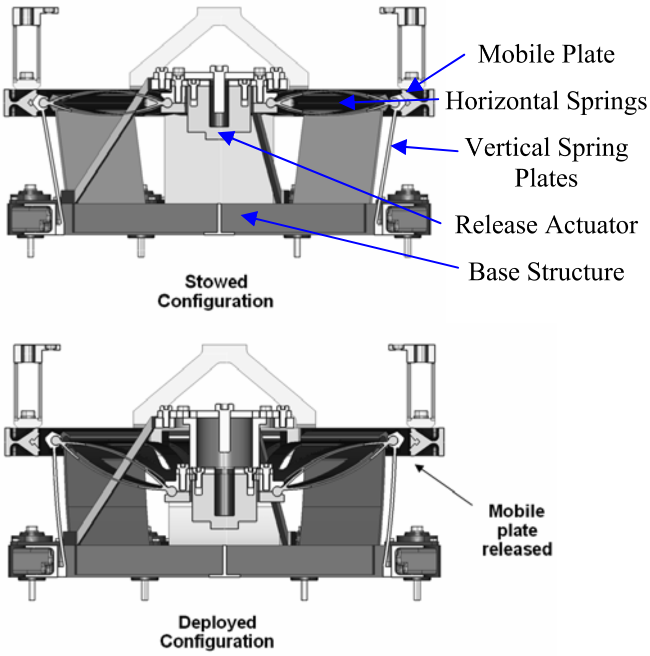


Figure 5. HDRM in stowed and deployed configuration (Principle Drawing)

The vertical spring plates have a curvature when relaxed, and are straight when pre-loaded. This causes high stiffness in the closed configuration.

The horizontal springs shall have high deformation under load. Different spring designs were investigated. On the breadboard model a curved shaped design was used (Fig. 5). During the life test it turned out that this curved shaped design is sensitive to bending loads introduced during the pre-loading sequence. Consequently for the following models this design was changed to a multiple bending lever design (Fig. 4) with higher bending stiffness to provide more robustness against integration loads.

4.3. Performance

The HDRM in essence forms a “frangible pipe” that is stiff during launch and collapses upon release. In stowed configuration the vertical spring plates form a pipe-like structure that rigidly supports the thruster. In deployed configuration the vertical spring plates retract to the inner side, allowing free rotation of the mobile plate. This allows a pointing angle of more than 20° in all directions.

The knuckle-lever type arrangement allows high holding force of the mobile plate, but at the same time allows low forces on the release actuator so that high margins on the holding forces and high motorization margins are assured during the whole opening sequence of the mechanism which in turn increases reliability of the assembly.

A single, central release nut is used. This facilitates very high reliability of the HDRM and also minimizes refurbishment effort during testing. The design as a self-standing unit allows easy integration of the mechanism on the spacecraft as a whole. This allows efficient integration and testing for the customer.

The majority of the parts of the HDRM are manufactured of thin walled Aluminum alloy resulting in a light weight design. This also makes the HDRM insensitive against pre-load changes resulting from temperature changes as it follows an isoexpansive design approach. The design consumes low height. The height of the HDRM drives the pendulum mode of the assembly, which can be kept low with this design.

The HDRM performance was confirmed by the tests. A patent for the design is pending.

5. SUMMARY AND CONCLUSION

The Bepi Colombo Electric Propulsion Thruster Pointing Assembly consists of 4 identical thruster pointing mechanisms and the drive electronics. Each mechanism supports an Electric Propulsion Thruster (QinetiQ T6) in stowed configuration during launch, by means of a dedicated Hold-Down and Release Mechanism (HDRM). Upon its release, the Pointing Mechanism Platform can be tilted around two perpendicular axes. This motion is facilitated by two geared rotary actuators.

Figure 6. Thruster Pointing Mechanism (TPM) with Thruster Mass Dummy and Sun-Shield attached.

The design-driving requirements for the Mechanism are firstly the high sensitivity of the electric propulsion thruster to mechanical loads, and secondly the pointing capability around its stowed configuration. The mechanism has not only to point the thruster, but also to protect it against the launch loads.

For the protection of the delicate thruster from launch loads a concept of "decoupling of frequencies" was successfully implemented: a very low lateral Eigenfrequency of the assembly of around 65 Hz was selected to minimize shock load transmission into the thruster, and a low frequency spacecraft panel. To cope with the low frequencies, an elastomer damping system is implemented which minimizes amplification in this low frequency area so that the sine loads can be sustained by the mechanism and the thruster.

A light-weight framework pointing arm made of one piece of Aluminum alloy allows a mass efficient design of the mechanism.

The pointing capability around the stowed configuration was attained via a central release nut together with a spring loaded knuckle-lever system which in essence forms a "frangible pipe" that is stiff during launch and collapses upon release.

6. REFERENCES

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7. REMARK & ACKNOWLEDGEMENT

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